Investigating the spectroscopy behavior of undetected 1*F*-wave charmed baryons

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In this work, we investigate the spectroscopic properties of 1*F*-wave charmed baryons, which have not yet been observed in experiments. We employ a nonrelativistic potential model and utilize the Gaussian expansion method to obtain the mass spectra of these charmed baryons. Additionally, we focus on the two-body Okubo-Zweig-Iizuka allowed strong decay behaviors, which plays a crucial role in characterizing the properties of these baryons. Our analyses of the mass spectra and two-body Okubo-Zweig-Iizuka allowed decay behaviors provides valuable insights for future experimental investigations. This study contributes to our understandings of the spectroscopic properties of 1*F*-wave charmed baryons.

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I. INTRODUCTION

In the last two decades, there has been a growing number of observed charmed baryon states in experimental studies. These states now form the primary constituent of the current charmed baryon family listed in the Particle Data Group (PDG) [1]. As an integral part of the broader hadron family, the observed charmed baryon states offer an excellent platform to investigate the formation of baryons from their quark components, which is intimately linked to low-energy strong interaction phenomena (see review articles [2–5]). A thorough investigation of charmed baryons can significantly enhance our understanding of the nonperturbative behavior of strong interaction.

The charmed baryon, composed of a charmed quark and two light quarks, is a representative few-body system exhibiting heavy quark symmetry, which makes it relatively simple compared to light baryons. In the past near fifty years, over 30 singly charmed baryons were observed in experiments [6–36]. Figure 1 presents the observed charmed baryon states. Intriguingly, treating the charmed baryon as a quasi two-body system by clustering the two light quarks leads to a mass spectrum that aligns with current experimental observations. The measured masses and widths allows readers to easily identify that the majority of *S*-, *P*-, and *D*-wave states are well established, indicating significant progress in hadron spectroscopy exploration [37–63]. This achievement is a result of the join efforts of experimental and theoretical colleagues. We express our gratitude to all involved. In fact, the construction of the charms baryon family is an ongoing story. Very recently, the LHC Collaboration made an exciting announcement regarding the observation of two enhancement structures, $\Omega_c(3185)$ and $\Omega_c(3327)$, in the $\Xi_c^+ K^-$ invariant mass spectrum [32]. The discovery of $\Omega_c(3327)$ is particularly significant as it promotes to explore the construction of *D*-wave charmed baryons [64–66]. As the LHC's high-luminosity updates continue, it is reasonable to expect that experimental access to more *D*-wave and higher orbital excitations of charmed baryons will become available. In light of these developments, theorists should devote greater attention to higher states of charmed baryon.

In this study, we investigate the spectroscopic properties of 1*F*-wave charmed baryons, which have yet to be observed in experiments. We employ a nonrelativistic potential model [65,67,68] and utilize the Gaussian

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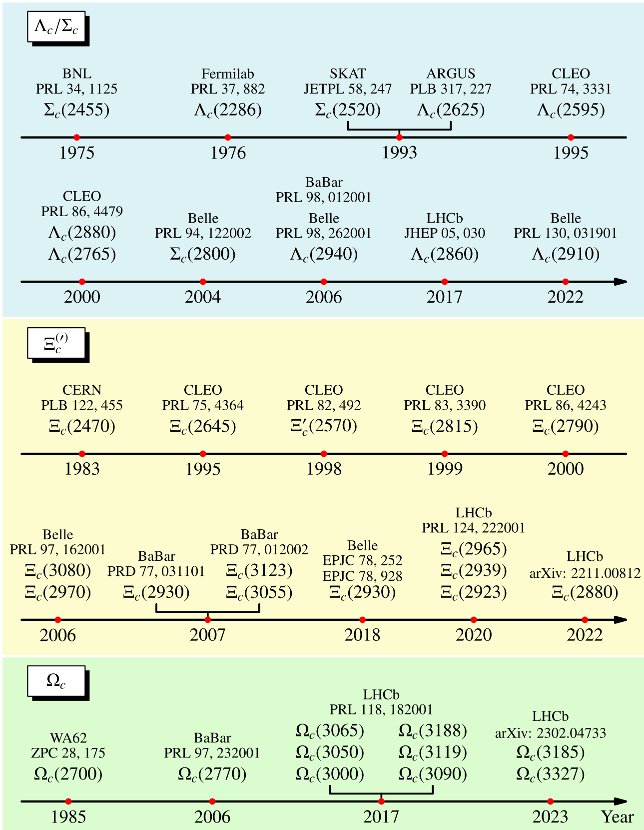

FIG. 1. The observed singly charmed baryons. The data presented in this paper is sourced from the following Refs. [6–32].

expansion method (GEM) [69] to obtain their mass spectrum. While the mass spectrum of F-wave charmed baryons is informative for future experimental searches, their two-body Okubo-Zweig-Iizuka (OZI) allowed strong decay behavior is even more crucial for characterizing their properties. To address this, we utilize the quark pair creation (QPC) [70–74] model, a well-established approach for analyzing the two-body OZI-allowed strong decay of singly charmed baryons [38,40–58]. By employing this approach, we can estimate their total decay width, which is approximately equal to their widths. Through our analysis of the mass spectrum and two-body OZI-allowed decay behavior of $1F$-wave charmed baryons, we can provide valuable insights for future experimental investigations.

This paper is structured as follows. Following the Introduction, we proceed to present the mass spectrum of $1F$ excited singly charmed baryons in Sec. II. Subsequently, in Sec. III, we perform calculations for the total and partial OZI-allowed two-body strong decay widths. Finally, we conclude with a concise summary in Sec. IV.

II. MASS SPECTRUM

As the first step, we utilize a nonrelativistic potential model to accurately compute the mass spectra of the F-wave excited singly charmed baryons. The Hamiltonian [65,67,68] is

$$\hat{H} = \sum_i \left(m_i + \frac{p_i^2}{2m_i}\right) + \sum_{i<j}\left(V_{ij}^{\mathrm{conf}} + V_{ij}^{\mathrm{hyp}} + V_{ij}^{\mathrm{so(cm)}} + V_{ij}^{\mathrm{so(tp)}}\right). \quad (1)$$

Here, we denote the mass and momentum of the ith constituent quark as m_i and p_i, respectively. The terms V_{ij}^{conf}, V_{ij}^{hyp}, $V_{ij}^{\mathrm{so(cm)}}$, and $V_{ij}^{\mathrm{so(tp)}}$ in Eq. (1) represent the confinement, hyperfine, color-magnetic, and Thomas-precession potentials, respectively. The specific forms of these interactions can be expressed as follows:

$$V_{ij}^{\mathrm{conf}} = -\frac{2}{3}\frac{\alpha_s}{r_{ij}} + \frac{b}{2}r_{ij} + \frac{1}{2}C, \quad (2)$$

$$V_{ij}^{\mathrm{hyp}} = \frac{2\alpha_s}{3m_i m_j}\left[\frac{8\pi}{3}\tilde{\delta}(r_{ij})\mathbf{s}_i\cdot\mathbf{s}_j + \frac{1}{r_{ij}^3}S(\mathbf{r},\mathbf{s}_i,\mathbf{s}_j)\right],$$
$$\tilde{\delta}(r) = \frac{\sigma^3}{\pi^{3/2}}\mathrm{e}^{-\sigma^2 r^2}, \qquad S(\mathbf{r},\mathbf{s}_i,\mathbf{s}_j) = \frac{3\mathbf{s}_i\cdot\mathbf{r}_{ij}\mathbf{s}_j\cdot\mathbf{r}_{ij}}{r_{ij}^2} - \mathbf{s}_i\cdot\mathbf{s}_j, \quad (3)$$

$$V_{ij}^{\mathrm{so(cm)}} = \frac{2\alpha_s}{3r_{ij}^3}\left(\frac{\mathbf{r}_{ij}\times\mathbf{p}_i\cdot\mathbf{s}_i}{m_i^2} - \frac{\mathbf{r}_{ij}\times\mathbf{p}_j\cdot\mathbf{s}_j}{m_j^2} - \frac{\mathbf{r}_{ij}\times\mathbf{p}_j\cdot\mathbf{s}_i - \mathbf{r}_{ij}\times\mathbf{p}_i\cdot\mathbf{s}_j}{m_i m_j}\right), \quad (4)$$

$$V_{ij}^{\mathrm{so(tp)}} = -\frac{1}{2r_{ij}}\frac{\partial H_{ij}^{\mathrm{conf}}}{\partial r_{ij}}\left(\frac{\mathbf{r}_{ij}\times\mathbf{p}_i\cdot\mathbf{s}_i}{m_i^2} - \frac{\mathbf{r}_{ij}\times\mathbf{p}_j\cdot\mathbf{s}_j}{m_j^2}\right). \quad (5)$$

In Eqs. (2)–(5), the parameters α_s, b, C, and σ represent the coupling constant of the one-gluon exchange, the strength of the linear confinement, the renormalized mass constant, and the smearing parameter, respectively.

As a conventional three-body system, it is advantageous to employ the ρ- and λ-modes to represent the Jacobi coordinates of a singly heavy baryon. In this context, the ρ-mode corresponds to the coordinate between the two light flavor quarks q_1 and q_2 ($q = u, d, s$). On the other hand, the λ-mode represents the vector connecting the heavy flavor quark Q_3 ($Q = c, b$) to the center-of-mass of the two light flavor quarks. The basis employed to derive the mass spectrum of the aforementioned $1F$-wave charmed baryons represents

$$|JM\rangle = |[[[s_{q_1}s_{q_2}]_{s_\ell}[n_\rho n_\lambda l_\rho l_\lambda]_L]_{j_\ell}s_{Q_3}]_{JM}\rangle. \quad (6)$$

In this context, s_{q_1}, s_{q_2}, and s_{Q_3} represent the spins of the quarks involved. Meanwhile, s_ℓ and j_ℓ denote the spin and

TABLE I. The parameters involved in the adopted potential model.

System	α_s	b (GeV^2)	σ (GeV)	C (GeV)
Λ_c/Σ_c	0.560	0.122	1.600	−0.633
$\Xi_c^{(\prime)}$	0.560	0.140	1.600	−0.693
Ω_c	0.578	0.144	1.732	−0.688
Meson	0.578	0.144	1.028	−0.685
$m_{u/d} = 0.370$ GeV $m_s = 0.600$ GeV $m_c = 1.880$ GeV				

total angular momentum of the light degree of freedom, respectively. The quantum numbers $n_{\rho/\lambda}$ and $l_{\rho/\lambda}$ refer to the radial and orbital components, respectively. The total orbital angular momentum of the system is denoted as L. Based on the spectroscopy of observed charmed baryons, these states can be categorized as λ-mode excitations. In this study, our primary focus remains on the λ-mode excited $1F$ states. Besides the degree-of-freedom in spin-spatial, a singly charmed baryon also has flavor wave function. Within the framework of $SU(3)$ flavor symmetry, the coupling of flavor wave functions can be decomposed as $3 \otimes 3 = \bar{3} \oplus 6$. The states in $\bar{3}_f$ include Λ_c^+, Ξ_c^+, and Ξ_c^0, while the 6_f states consist of Σ_c^+, Σ_c^0, Σ_c^{++}, $\Xi_c^{\prime +}$, $\Xi_c^{\prime 0}$, and Ω_c^0. It is worth noting that the flavor wave functions of the two light quarks are antisymmetrical for $\bar{3}_f$ and symmetrical for 6_f. For the sake of simplicity, we will omit their isospin partners in the subsequent discussions. Adhering to the Pauli principle, we present the basis states in Table II. The λ-mode excited $1F$ states of Λ_c or Ξ_c consist of two states, while the λ-mode excited $1F$ states of Σ_c, Ξ_c', or Ω_c encompass six states.

Using the Gaussian expansion method [69], we can solve the three body Schrödinger equations with the above potentials. According to the mass spectra of the observed singly charmed baryons, we have derived the parameters of the potential model and compiled them in Table I. Additionally, we have compared our calculated results with the masses of the observed states, as depicted in Fig. 2. Our calculations for the $1S$, $2S$, $1P$, and $1D$ states exhibit a remarkable agreement with the corresponding experimental candidates. Similar results were also obtained in previous theoretical works [75–83]. Building upon these initial considerations, we have proceeded to calculate the masses of the λ-mode $1F$ excited singly charmed baryons. In accordance with the Pauli principle, we present the basis states in Table II. The λ-mode excited $1F$ states of Λ_c or Ξ_c consist of two states, while the λ-mode excited $1F$ states of Σ_c, Ξ_c', or Ω_c encompass six states. The numerical results for these states are provided in Table III.

III. OZI-ALLOWED TWO-BODY STRONG DECAYS

Since the decay behavior can provide valuable information in the search for these states, it is essential to perform systematic calculations for the decay widths. In this study, we utilize the QPC model [70–74] to calculate the partial and total decay widths of λ-mode $1F$ excited singly charmed baryons. The corresponding transition operator is used in these calculations, i.e.,

$$\hat{\mathcal{T}} = -3\gamma \sum_m \langle 1, m; 1, -m|0, 0\rangle \int \mathrm{d}^3\mathbf{p}_i \mathrm{d}^3\mathbf{p}_j \delta(\mathbf{p}_i + \mathbf{p}_j) \times \mathcal{Y}_1^m\left(\frac{\mathbf{p}_i - \mathbf{p}_j}{2}\right) \omega_0^{(i,j)} \phi_0^{(i,j)} \chi_{1,-m}^{(i,j)} b_i^\dagger(\mathbf{p}_i) d_j^\dagger(\mathbf{p}_j), \tag{7}$$

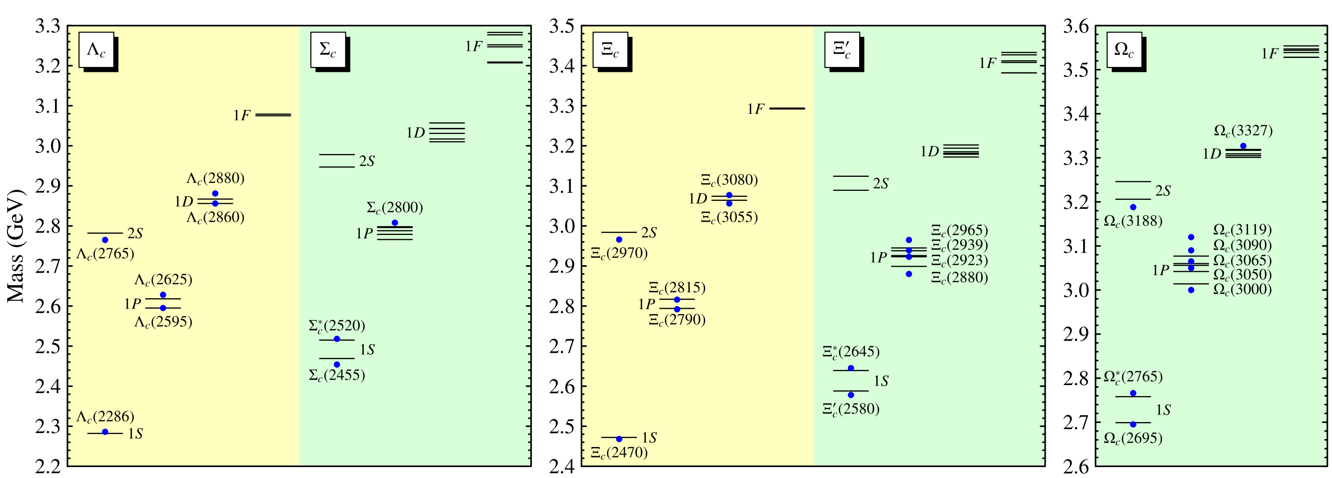

FIG. 2. The calculated masses of the singly charmed baryons and the comparison with experimental data. The short lines in the graph represent the calculated results, while the blue points on the graph are obtained from the experimental data, which is taken from the PDG [1].

TABLE II. The basis of λ-mode excited $1F$ singly charmed baryons.

Symmetry	States	J	s_ℓ	n_ρ	n_λ	l_ρ	l_λ	L	j_ℓ
$\bar{3}_f$	$\Lambda_c/\Xi_c(1F,5/2^-)$	$\frac{5}{2}$	0	0	0	0	3	3	3
	$\Lambda_c/\Xi_c(1F,7/2^-)$	$\frac{7}{2}$	0	0	0	0	3	3	3
6_f	$\Sigma_{c2}/\Xi'_{c2}/\Omega_{c2}(1F,3/2^-)$	$\frac{3}{2}$	1	0	0	0	3	3	2
	$\Sigma_{c2}/\Xi'_{c2}/\Omega_{c2}(1F,5/2^-)$	$\frac{5}{2}$	1	0	0	0	3	3	2
	$\Sigma_{c3}/\Xi'_{c3}/\Omega_{c3}(1F,5/2^-)$	$\frac{5}{2}$	1	0	0	0	3	3	3
	$\Sigma_{c3}/\Xi'_{c3}/\Omega_{c3}(1F,7/2^-)$	$\frac{7}{2}$	1	0	0	0	3	3	3
	$\Sigma_{c4}/\Xi'_{c4}/\Omega_{c4}(1F,7/2^-)$	$\frac{7}{2}$	1	0	0	0	3	3	4
	$\Sigma_{c4}/\Xi'_{c4}/\Omega_{c4}(1F,9/2^-)$	$\frac{9}{2}$	1	0	0	0	3	3	4

TABLE III. A comparison of predicted masses for F-wave singly charmed baryons from various studies. Here, the listed masses are in units of MeV.

States	Our	Ref. [81]	Ref. [80]	States	Our	Ref. [81]	Ref. [82]	States	Our	Ref. [81]	Ref. [80]
$\Lambda_c(1F,5/2^-)$	3075	3097	3104	$\Xi_c(1F,5/2^-)$	3292	3278	3289				
$\Lambda_c(1F,7/2^-)$	3079	3078	3111	$\Xi_c(1F,7/2^-)$	3295	3292	3294				
$\Sigma_{c2}(1F,3/2^-)$	3276	3288	3299	$\Xi'_{c2}(1F,3/2^-)$	3427	3418	3424	$\Omega_{c2}(1F,3/2^-)$	3540	3533	3525
$\Sigma_{c2}(1F,5/2^-)$	3283	3254	3304	$\Xi'_{c2}(1F,3/2^-)$	3433	3394	3428	$\Omega_{c2}(1F,5/2^-)$	3547	3515	3528
$\Sigma_{c3}(1F,5/2^-)$	3247	3283	3299	$\Xi'_{c3}(1F,3/2^-)$	3408	3408	3424	$\Omega_{c3}(1F,5/2^-)$	3532	3522	3525
$\Sigma_{c3}(1F,7/2^-)$	3252	3227	3305	$\Xi'_{c3}(1F,3/2^-)$	3412	3373	3428	$\Omega_{c3}(1F,7/2^-)$	3537	3498	3529
$\Sigma_{c4}(1F,7/2^-)$	3207	3253	3299	$\Xi'_{c4}(1F,3/2^-)$	3382	3393	3423	$\Omega_{c4}(1F,7/2^-)$	3521	3514	3524
$\Sigma_{c4}(1F,9/2^-)$	3209	3209	3305	$\Xi'_{c4}(1F,3/2^-)$	3383	3357	3428	$\Omega_{c4}(1F,9/2^-)$	3520	3485	3529

where $\omega_0^{(i,j)} = (r\bar{r} + g\bar{g} + b\bar{b})/\sqrt{3}$, $\phi_0^{(i,j)} = (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$, $\chi_{1,-m}^{(i,j)}$, and $\mathcal{Y}$ are the color-singlet, flavor-singlet, spin-1, and spatial functions for the quark pair created from the vacuum, respectively. The γ is a dimensionless parameter, which is determined by the widths of the well established states. Then in the decay process $A \to BC$, the partial wave amplitude could be written as

$$\mathcal{M}_{A\to BC}^{L_{BC}S_{BC}}(p) = \langle BC, L_{BC}S_{BC}, p|\hat{\mathcal{T}}|A\rangle, \tag{8}$$

where L_{BC} and S_{BC} are the relative orbital angular momentum and spin between the final BC. In Eq. (8), the variable p represents the momentum of the outgoing baryon B. The partial decay width can be obtained by performing the following calculation:

$$\Gamma_{A\to BC} = 2\pi \frac{E_B E_C}{M_A} p \sum_{L_{BC}S_{BC}} |\mathcal{M}_{A\to BC}^{L_{BC}S_{BC}}(p)|^2, \tag{9}$$

where $E_B = \sqrt{M_B^2 + p^2}$ and $E_C = \sqrt{M_C^2 + p^2}$ are the energies of the baryon B and meson C, respectively.

To calculate the overlap of the spatial part in Eq. (8), we utilize the following reduced wave functions:

$$\psi_{n_\rho n_\lambda l_\rho l_\lambda LM}(\boldsymbol{\rho},\boldsymbol{\lambda}) \approx R_{n_\rho l_\rho}^p(\beta_\rho, p_\rho) R_{n_\lambda l_\lambda}^p(\beta_\lambda, p_\lambda) \times \sum_{m_\rho m_\lambda} C_{l_\rho m_\rho, l_\lambda m_\lambda}^{LM} Y_{l_\rho m_\rho}(\Omega_{\mathbf{p}_\rho}) Y_{l_\lambda m_\lambda}(\Omega_{\mathbf{p}_\lambda}), \tag{10}$$

where

$$R_{nl}^p(\beta, P) = \frac{(-1)^n(-\mathrm{i})^l}{\beta^{\frac{3}{2}+l}} \sqrt{\frac{2n!}{\Gamma(n+l+\frac{3}{2})}} L_n^{l+\frac{1}{2}}(P^2/\beta^2) \mathrm{e}^{-\frac{P^2}{2\beta^2}} P^l \tag{11}$$

is radial part of the simple harmonic oscillator (SHO) wave function. In Eqs. (10) and (11), the β is a characteristic parameter to represent the simple harmonic oscillator. Using the approaches described in Refs. [40,43,65], we determine the values of β and present them in Table IV.

Based on the obtained parameters, we determine the value of the parameter $\gamma = 9.58$ from the measured width of $\Sigma_c^*(2520)$ [1]. This value of γ is employed in the global calculations conducted in this study.

A. $\Lambda_c(1F)$ states

Table V presents the calculated widths of $\Lambda_c(1F,5/2^-)$ and $\Lambda_c(1F,7/2^-)$ to be approximately 43.3 MeV and

TABLE IV. The β values used in this work.

States	β_ρ	β_λ	States	β_ρ	β_λ	States	β
$\Lambda_c(1S)$	0.290	0.344	$\Xi_c(1S)$	0.301	0.383	π	0.409
$\Lambda_c(2S)$	0.251	0.185	$\Xi_c(2S)$	0.258	0.207	K	0.385
$\Lambda_c(1P)$	0.271	0.237	$\Xi_c(1P)$	0.281	0.265	K^*	0.259
$\Lambda_c(2P)$	0.256	0.153	$\Xi_c(2P)$	0.264	0.173	D	0.357
$\Lambda_c(1D)$	0.259	0.182	$\Xi_c(1D)$	0.268	0.203	D^*	0.307
$\Lambda_c(1F)$	0.254	0.152	$\Xi_c(1F)$	0.262	0.167		
$\Sigma_c(1S)$	0.220	0.336	$\Xi_c'(1S)$	0.252	0.383		
$\Sigma_c^*(1S)$	0.212	0.315	$\Xi_c^*(1S)$	0.243	0.358		
$\Sigma_c(2S)$	0.188	0.186	$\Xi_c'(2S)$	0.212	0.210		
$\Sigma_c^*(2S)$	0.190	0.174	$\Xi_c^*(2S)$	0.216	0.202		
$\Sigma_c(1P)$	0.210	0.238	$\Xi_c'(1P)$	0.240	0.270		
$\Sigma_c(1D)$	0.198	0.185	$\Xi_c'(1D)$	0.226	0.206		
$\Sigma_c(1F)$	0.191	0.152	$\Xi_c'(1F)$	0.218	0.168		
$\Omega_c(1S)$	0.288	0.420	N	0.280	0.324		
$\Omega_c^*(1S)$	0.275	0.389	Δ	0.249	0.288		
$\Omega_c(2S)$	0.230	0.229	Λ	0.281	0.285		
$\Omega_c^*(2S)$	0.236	0.217	Σ	0.223	0.301		
$\Omega_c(1P)$	0.273	0.294	Σ^*	0.206	0.262		
$\Omega_c(1D)$	0.254	0.223	Ξ	0.287	0.317		
$\Omega_c(1F)$	0.244	0.181	Ξ^*	0.258	0.265		

TABLE V. The partial and total widths of the $\Lambda_c(1F)$ in units of MeV. The M_f represents the masses of the final singly charmed baryons. In the table, channels with small partial widths are listed in the column labeled "…" to indicate their negligible contribution to the overall decay process.

Decay channels	M_f (MeV)	$\Lambda_c(1F,5/2^-)$	$\Lambda_c(1F,7/2^-)$
$\Sigma_c(1S,3/2^+)\pi$	2520	0.5	0.8
$\Sigma_{c2}(1P,3/2^-)\pi$	2779	9.5	0.2
$\Sigma_{c2}(1P,5/2^-)\pi$	2796	0.8	9.5
ND		9.9	11.8
ND^*		21.6	40.2
…		1.0	0.8
Total		43.3	63.3

63.3 MeV, respectively. It is worth noting that we observe a significant contribution from the ND^* decay channel in both states, as indicated by the large branching ratios, i.e.,

$$\mathrm{Br}[\Lambda_c(1F,5/2^-)\to ND^*]\approx 49.9\%,$$
$$\mathrm{Br}[\Lambda_c(1F,7/2^-)\to ND^*]\approx 63.5\%. \qquad (12)$$

The observation of the ND^* channel in the calculated widths of $\Lambda_c(1F,5/2^-)$ and $\Lambda_c(1F,7/2^-)$ is noteworthy and may have connections to previous experimental observations. The LHCb Collaboration has reported the observation of two $\Lambda_c(1D)$ candidates, the $\Lambda_c(2860)$ and $\Lambda_c(2880)$, as well as a $\Lambda_c(2P)$ candidate, the $\Lambda_c(2940)$, in the $\Lambda_b^0\to\Lambda_c^+(X)\pi^-\to D^0p\pi^-$ decay channel [15]. Given that the $\Lambda_c(1F)$ states exhibit similar excited modes to the $\Lambda_c(1D)$ and $\Lambda_c(2P)$ states, experimentalists could search for $\Lambda_c(1F)$ states in the chain process $\Lambda_b^0\to\Lambda_c^+(1F)\pi^-\to D^{*0}p\pi^-$. This approach may provide valuable insights into the existence and properties of $\Lambda_c(1F)$ states.

TABLE VI. The partial and total widths of the $\Xi_c(1F)$ in units of MeV. In the calculation of partial decay widths, the M_f denotes the masses of the final singly charmed baryons. The column marked with "⋯" includes channels with small partial widths. A value of "0.0" indicates that the width is less than 0.1 MeV.

Decay channels	M_f (MeV)	$\Xi_c(1F,5/2^-)$	$\Xi_c(1F,7/2^-)$
$\Xi_{c2}'(1P,3/2^-)\pi$	2926	1.5	0.1
$\Xi_{c2}'(1P,5/2^-)\pi$	2945	0.2	1.6
$\Sigma_c(1S,1/2^+)\bar{K}$	2455	0.7	0.7
$\Sigma_c(1S,3/2^+)\bar{K}$	2520	1.2	1.7
$\Sigma_{c2}(1P,3/2^-)\bar{K}$	2779	4.4	0.0
$\Sigma_{c2}(1P,5/2^-)\bar{K}$	2796	0.0	0.6
ΛD		0.5	2.1
ΣD		10.0	22.9
ΛD^*		4.0	5.2
ΣD^*		28.3	54.3
⋯		0.9	0.9
Total		51.7	90.1

B. $\Xi_c(1F)$ states

In the realm of orbital excited Ξ_c states, the established candidates include the $1P$ and $1D$ states. However, the $\Xi_c(1F)$ states have not been observed yet. In this study, we provide predictions for the masses and widths of the $\Xi_c(1F)$ states, which could be instrumental in the search for higher orbital excited Ξ_c states by experimentalists. As shown in Table VI, the total widths of $\Xi_c(1F,5/2^-)$ and $\Xi_c(1F,7/2^-)$ are projected to be 51.7 and 90.1 MeV, respectively. These results indicate that the $\Xi_c(1F,7/2^-)$ state is expected to exhibit large widths but the $\Xi_c(1F,5/2^-)$ state is not so broad. Furthermore, it is worth exploring the ΣD and ΣD^* channels as potential avenues for the observation of the $\Xi_c(1F)$ states. For the ΣD^* channel, the calculated branching ratios of both $\Xi_c(1F,5/2^-)$ and $\Xi_c(1F,7/2^-)$ are larger than 50%. We recommend conducting a search for the $\Xi_c(1F)$ states in the aforementioned channels.

C. $\Sigma_c(1F)$ states

In Table VII, the calculated widths of $\Sigma_{c2}(1F,3/2^-)$, $\Sigma_{c2}(1F,5/2^-)$, $\Sigma_{c3}(1F,5/2^-)$, $\Sigma_{c3}(1F,7/2^-)$, and $\Sigma_{c4}(1F,7/2^-)$ fall within the range of approximately 70 to 110 MeV. However, the predicted width of $\Sigma_{c4}(1F,9/2^-)$ is smaller, with a value of 51.0 MeV, compared to the widths of the former five states.

Upon careful analysis of their decay modes, it is observed that the $\Lambda_c(1S)\pi$ and $\Sigma_c(1S)\pi$ channels have significantly depressed partial widths, which are absorbed

TABLE VII. The partial and total widths of the $\Sigma_c(1F)$ in units of MeV. The M_f corresponds to the masses of the final singly charmed baryons. Channels with small partial widths are marked with "…" in the respective column to indicate their negligible contribution. A value of "0.0" indicates that the partial width is less than 0.1 MeV. The symbol "✗" is used to denote that the coupling is forbidden. If the mass of a initial state is below the threshold for a particular decay channel, it is denoted by "–".

Decay channels	M_f (MeV)	$\Sigma_{c2}(1F,3/2^-)$	$\Sigma_{c2}(1F,5/2^-)$	$\Sigma_{c3}(1F,5/2^-)$	$\Sigma_{c3}(1F,7/2^-)$	$\Sigma_{c4}(1F,7/2^-)$	$\Sigma_{c4}(1F,9/2^-)$
$\Lambda_c(2S,1/2^+)\pi$	2766	7.7	8.5	✗	✗	6.5	6.7
$\Lambda_c(1P,1/2^-)\pi$	2592	3.5	0.0	1.8	1.0	8.1	1.7
$\Lambda_c(1P,3/2^-)\pi$	2628	0.5	3.3	2.0	2.8	4.4	10.9
$\Lambda_c(2P,1/2^-)\pi$	3004	3.6	0.0	0.1	0.1	0.1	0.0
$\Lambda_c(2P,3/2^-)\pi$	2940	2.8	15.4	0.5	0.8	0.2	0.9
$\Lambda_c(1D,3/2^+)\pi$	2856	14.5	0.7	17.4	3.1	9.1	0.4
$\Lambda_c(1D,5/2^+)\pi$	2881	1.5	13.1	4.3	17.2	1.2	8.9
$\Lambda_c(1F,5/2^-)\pi$	3075	17.8	1.0	3.6	0.2	–	–
$\Lambda_c(1F,7/2^-)\pi$	3079	0.0	17.8	0.2	3.8	–	–
$\Sigma_{c0}(1P,1/2^-)\pi$	2788	✗	✗	3.0	3.1	✗	✗
$\Sigma_{c1}(1P,1/2^-)\pi$	2766	0.1	1.0	3.9	2.3	2.4	0.1
$\Sigma_{c1}(1P,3/2^-)\pi$	2798	1.2	1.1	4.0	5.6	0.7	2.5
$\Sigma_{c2}(1P,3/2^-)\pi$	2779	1.6	1.6	1.9	0.5	5.6	1.0
$\Sigma_{c2}(1P,5/2^-)\pi$	2796	2.1	2.4	0.6	2.9	1.6	5.5
$\Sigma_{c2}(1D,3/2^+)\pi$	3030	18.3	1.6	1.1	0.2	0.2	0.0
$\Sigma_{c2}(1D,5/2^+)\pi$	3043	1.5	19.9	0.2	1.0	0.0	0.1
$\Sigma_{c3}(1D,5/2^+)\pi$	3010	3.6	0.7	25.4	0.3	1.5	0.1
$\Sigma_{c3}(1D,7/2^+)\pi$	3017	0.6	3.7	0.3	26.2	0.1	1.3
ND		0.0	0.0	0.0	1.6	0.1	3.6
ΔD		4.8	15.0	14.0	7.4	23.9	1.3
ND^*		0.5	1.0	4.7	3.5	7.6	4.3
ΔD^*		1.9	4.8	0.1	0.6	–	–
ΣD_s		2.5	0.1	1.0	0.0	0.0	0.0
…		2.3	2.2	3.3	3.0	1.7	1.7
Total		92.9	114.9	93.4	87.2	75.0	51.0

within the "…" category in Table VII. However, it is worth noting that $\Sigma_{c2}(1F,3/2^-)$, $\Sigma_{c2}(1F,5/2^-)$, $\Sigma_{c3}(1F,5/2^-)$, and $\Sigma_{c3}(1F,7/2^-)$ can decay into $\Sigma_{c2}(1D,3/2^+)\pi$, $\Sigma_{c2}(1D,5/2^+)\pi$, $\Sigma_{c3}(1D,5/2^+)\pi$, and $\Sigma_{c3}(1D,7/2^+)\pi$ states, respectively, in an S-wave. Consequently, the $\Sigma_c(1D)\pi$ channels play crucial roles in the decay of these states. Besides the $\Sigma_c(1D)\pi$, the $\Sigma_c(1P)\pi$ channels also work in the decays of $\Sigma_c(1F)$. According to the calculations of Refs. [40,84,85], it is potential to observe $\Sigma_c(1P)$ and $\Sigma_c(1D)$ states by the $\Lambda_c\pi$ channel. In this way, the $\Sigma_c(1P)\pi$ and $\Sigma_c(1D)\pi$ then could decay into $\Lambda_c\pi\pi$, which may be an approach to search for the $\Sigma_c(1F)$ states.

In the case of $\Sigma_c(1F)$ states, both the spin and flavor wave functions of the light quarks exhibit symmetry. Hence, in the ΔD channel, the two light quarks can be considered as a single cluster during the decay process, indicating that the ΔD channel may have a substantial partial width. For instance, ΔD accounts for approximately 31.9% of the branching ratio for $\Sigma_{c4}(1F,7/2^-)$. Since the Δ could decay into $p\pi$, the observation of ΔD through $Dp\pi$ could provide a potential avenue for the search of $\Sigma_c(1F)$.

Regarding $\Sigma_{c4}(1F,9/2^-)$, significant contributions arise from $\Lambda_c(1P,3/2^-)\pi$ and $\Lambda_c(1D,5/2^-)\pi$ channels. Given that $\Lambda_c(1P,3/2^-)$ and $\Lambda_c(1D,5/2^-)$ are well-established narrow states, searching for the $\Sigma_{c4}(1F,9/2^-)$ state in $\Lambda_c(1P,3/2^-)\pi$ and $\Lambda_c(1D,5/2^-)\pi$ channels would be a viable approach.

D. $\Xi_c'(1F)$ states

According to Table VIII, the calculated widths of $\Xi_{c2}'(1F,3/2^-)$ and $\Xi_{c4}'(1F,9/2^-)$ are 51.8 and 69.6 MeV, respectively. The $\Xi_{c2}'(1F,5/2^-)$, $\Xi_{c3}'(1F,5/2^-)$, $\Xi_{c3}'(1F,7/2^-)$, $\Xi_{c3}'(1F,7/2^-)$ may be broad states, which predicted widths are roughly in 90–100 MeV.

For all six $\Xi_c'(1F)$ states, the partial widths of $\Xi_c^{(\prime)}(1S)\pi$, $\Lambda_c(1S)\bar{K}$, and $\Sigma_c(1S)\bar{K}$ are extremely small. Consequently, it may be challenging to observe $\Xi_c'(1F)$ in these channels. However, our calculations indicate that $\Sigma_c(1P)\bar{K}$ channels may play a significant role for some states. For instance, $\Sigma_{c2}(1P,3/2^-)\bar{K}$ and $\Sigma_{c2}(1P,5/2^-)\bar{K}$ exhibit considerable partial widths for $\Xi_{c3}'(1F,5/2^-)$ and $\Xi_{c3}'(1F,7/2^-)$, respectively. Additionally, according

TABLE VIII. The partial and total widths of the $\Xi'_c(1F)$ in units of MeV. The conventions are the same as that of Table VII.

Decay channels	M_f (MeV)	$\Xi'_{c2}(1F,3/2^-)$	$\Xi'_{c2}(1F,5/2^-)$	$\Xi'_{c3}(1F,5/2^-)$	$\Xi'_{c3}(1F,7/2^-)$	$\Xi'_{c4}(1F,7/2^-)$	$\Xi'_{c4}(1F,9/2^-)$
$\Xi_c(2S,1/2^+)\pi$	2970	0.7	0.9	✗	✗	1.6	1.6
$\Xi_c(1P,1/2^-)\pi$	2790	0.8	0.0	0.7	0.4	4.7	0.3
$\Xi_c(1P,3/2^-)\pi$	2815	0.2	0.7	0.8	1.1	1.7	5.7
$\Xi_c(1D,3/2^+)\pi$	3055	4.3	0.7	7.5	1.1	7.1	0.1
$\Xi_c(1D,5/2^+)\pi$	3080	0.9	3.2	1.4	6.5	0.6	5.9
$\Xi'_{c1}(1P,3/2^-)\pi$	2938	0.3	0.3	0.8	1.2	0.2	0.7
$\Xi'_{c2}(1P,3/2^-)\pi$	2926	0.3	0.3	0.6	0.0	1.4	0.2
$\Xi'_{c2}(1P,5/2^-)\pi$	2945	0.3	0.4	0.1	0.8	0.4	1.3
$\Xi'_{c2}(1D,3/2^+)\pi$	3181	5.7	0.3	0.4	0.1	0.2	0.0
$\Xi'_{c2}(1D,5/2^+)\pi$	3194	0.3	6.1	0.1	0.3	0.0	0.1
$\Xi'_{c3}(1D,5/2^+)\pi$	3172	0.6	0.1	8.0	0.1	0.7	0.0
$\Xi'_{c3}(1D,7/2^+)\pi$	3179	0.1	0.6	0.1	8.3	0.1	0.5
$\Lambda_c(1S,1/2^+)\bar{K}$	2286	0.0	0.0	✗	✗	1.2	1.2
$\Lambda_c(2S,1/2^+)\bar{K}$	2766	1.7	2.1	✗	✗	1.7	1.7
$\Lambda_c(1P,1/2^-)\bar{K}$	2592	2.2	0.0	2.2	1.3	8.5	1.7
$\Lambda_c(1P,3/2^-)\bar{K}$	2628	0.5	1.6	2.4	3.3	4.3	11.1
$\Lambda_c(1D,3/2^+)\bar{K}$	2856	5.0	1.1	4.5	0.7	1.0	0.0
$\Lambda_c(1D,5/2^+)\bar{K}$	2881	0.9	10.1	0.3	1.9	0.0	0.0
$\Sigma_c(1S,1/2^+)\bar{K}$	2455	0.1	0.0	0.3	1.4	1.1	0.7
$\Sigma_c(1S,3/2^+)\bar{K}$	2520	0.2	0.3	2.6	1.9	1.6	2.0
$\Sigma_{c0}(1P,1/2^-)\bar{K}$	2788	✗	✗	1.8	2.0	✗	✗
$\Sigma_{c1}(1P,1/2^-)\bar{K}$	2766	5.4	0.8	4.4	2.6	1.9	0.0
$\Sigma_{c1}(1P,3/2^-)\bar{K}$	2798	2.4	10.4	3.1	4.6	0.3	1.2
$\Sigma_{c2}(1P,3/2^-)\bar{K}$	2779	4.4	2.3	19.4	0.2	3.9	0.7
$\Sigma_{c2}(1P,5/2^-)\bar{K}$	2796	2.6	5.5	1.8	24.0	0.8	2.9
$\Lambda_c(1S,1/2^+)\bar{K}^*$	2286	0.2	0.2	1.1	1.2	0.7	0.7
ΛD		0.0	0.0	0.0	1.9	0.1	4.5
ΣD		0.0	0.0	0.0	2.9	0.1	6.7
$\Sigma^* D$		5.0	30.7	16.4	18.0	34.5	5.7
ΛD^*		0.5	1.0	5.7	4.0	10.6	6.0
ΣD^*		1.8	3.8	7.4	6.8	10.6	6.0
$\Sigma^* D^*$		3.1	7.4	1.0	3.8	–	–
⋯		1.3	1.7	3.8	2.6	2.1	0.4
Total		51.8	92.6	98.7	105.0	103.7	69.6

to the calculations in Ref. [40], the dominant decay mode of both $\Sigma_{c2}(1P,3/2^-)$ and $\Sigma_{c2}(1P,5/2^-)$ is $\Lambda_c\pi$. Therefore, it is possible to observe $\Xi'_c(1F)$ in the $\Lambda_c\bar{K}\pi$ channel. For the $\Xi'_{c4}(1F,9/2^-)$, the $\Lambda_c(1P,3/2^-)\bar{K}$ occupies considerable branching ratios, which provide some clue to search for $\Xi'_c(1F)$.

We also notice that the widths of the $\Sigma^* D$ channel are considerable for some $\Xi'_c(1F)$ states. For example, the branching ratio of $\Sigma^* D$ for $\Xi'_{c4}(1F,7/2^-)$ is approximately 33.3%. It may be also a approach to search for $\Xi'_c(1F)$ in $\Sigma^* D$ channel.

E. $\Omega_c(1F)$ states

According to Table IX, it can be observed that the $\Xi_c^{(\prime,*)}(1S)\bar{K}$ channels only contribute small fractions to the decay processes. However, in the $\Xi^{(*)}D^{(*)}$ channels, the c quark acts as a spectator while the ss quarks form a cluster. Therefore, it is expected that the $\Xi^{(*)}D^{(*)}$ channels would have considerable partial widths. The numerical results also indicate that the ΞD, $\Xi^* D$, and $\Xi^* D^*$ channels play crucial roles in the decays of $\Omega_c(1F)$ states. Thus, the $\Xi^{(*)}D^{(*)}$ channels are promising channels for the observation of $\Omega_c(1F)$ states.

For the $\Omega_{c2}(1F,3/2^-)$ state, the predicted width is 73.0 MeV. Notably, the $\Xi^* D$ and ΞD^* channels are identified as two important decay channels with significant branching ratios

$$\mathrm{Br}[\Omega_{c2}(1F,3/2^-)\to\Xi^* D]\approx 30.8\%,$$
$$\mathrm{Br}[\Omega_{c2}(1F,3/2^-)\to\Xi D^*]\approx 42.2\%. \quad (13)$$

However, it is worth noting that the predicted widths of $\Omega_{c2}(1F,5/2^-)$, $\Omega_{c3}(1F,5/2^-)$, $\Omega_{c3}(1F,7/2^-)$, $\Omega_{c4}(1F,7/2^-)$, and $\Omega_{c4}(1F,9/2^-)$ states are relatively

TABLE IX. The partial and total widths of the $\Omega_c(1F)$ in units of MeV. The conventions are consistent with Table VII.

Decay channels	M_f (MeV)	$\Omega_{c2}(1F,3/2^-)$	$\Omega_{c2}(1F,5/2^-)$	$\Omega_{c3}(1F,5/2^-)$	$\Omega_{c3}(1F,7/2^-)$	$\Omega_{c4}(1F,7/2^-)$	$\Omega_{c4}(1F,9/2^-)$
$\Xi_c(1S,1/2^+)\bar{K}$	2470	0.0	0.0	✗	✗	1.7	1.7
$\Xi_c(1P,1/2^-)\bar{K}$	2790	0.1	0.7	2.9	1.7	19.2	0.7
$\Xi_c(1P,3/2^-)\bar{K}$	2815	1.6	1.6	2.9	4.1	5.9	20.7
$\Xi_c'(1S,3/2^+)\bar{K}$	2645	0.2	0.3	1.1	1.0	0.7	0.9
$\Xi_{c0}'(1P,1/2^-)\bar{K}$	2923	✗	✗	1.1	1.2	✗	✗
$\Xi_{c1}'(1P,1/2^-)\bar{K}$	2899	7.0	0.3	2.2	1.3	1.6	0.0
$\Xi_{c1}'(1P,3/2^-)\bar{K}$	2938	1.9	10.5	1.1	1.7	0.2	0.7
$\Xi_{c2}'(1P,3/2^-)\bar{K}$	2926	3.5	0.8	18.7	0.0	1.8	0.3
$\Xi_{c2}'(1P,5/2^-)\bar{K}$	2945	0.8	3.8	1.4	20.5	0.3	1.1
$\Xi_c(1S,1/2^+)\bar{K}^*$	2470	0.6	0.6	1.2	1.3	0.4	0.4
ΞD		3.4	0.1	2.5	27.9	1.0	64.2
$\Xi^* D$		22.5	58.5	61.5	38.9	117.3	13.7
ΞD^*		30.8	68.5	73.6	77.2	110.7	61.3
⋯		0.6	1.1	0.4	0.7	0.6	0.4
Total		73.0	146.8	170.6	177.5	261.4	166.1

large, exceeding 100 MeV. This indicates that these states are quite broad compared to the other $\Omega_c(1F)$ states discussed earlier.

IV. SUMMARY

In this study, we have conducted an investigation into the spectroscopy behavior of undetected $1F$-wave charmed baryons. By employing a nonrelativistic potential model and the QPC model, we have predicted the masses, widths, and decay channels of these focused states.

Our results indicate that the $1F$-wave charmed baryons exhibit interesting spectroscopic properties. The calculated widths of the different states vary within a certain range, with some states being relatively narrow. These narrow states offer potential opportunities for experimental detection.

We have analyzed the decay modes of the $1F$-wave charmed baryons and identified the dominant and suppressed decay channels. Our findings suggest that certain channels may play significant roles in the decays of these states. These channels provide promising avenues for the observation of $1F$-wave charmed baryons.

Furthermore, we have discussed the implications of our results for experimental searches. We propose specific channels and decay modes that experimentalists can target in their search for these elusive states, i.e.,

(1) The decay modes involving a $1S$ singly charmed baryon [$\Lambda_c(1S)$, $\Sigma_c(1S)$, and $\Xi_c^{(\prime)}(1S)$] with a pseudoscalar meson (π and $\bar{K}$) have small branching ratios for these $1F$ states.

(2) The channels that include a light flavor baryon with a heavy flavor meson show potential for observing these $1F$ states.

(3) It is recommended to search for $\Sigma_c(1F)$ in the $\Lambda_c\pi\pi$, $\Lambda_c(1P)\pi$, and $\Lambda_c(1D)\pi$ channels, and search for $\Xi_c'(1F)$ in $\Lambda_c\bar{K}\pi$ and $\Lambda_c(1P)\bar{K}$ channels.

By focusing on these suggested channels, it may be possible to detect and study the properties of $1F$-wave charmed baryons, thereby enhancing our understanding of the charmed baryon spectroscopy.

Overall, our study contributes to the ongoing efforts in exploring and characterizing the spectroscopy of charmed baryons, particularly in the $1F$-wave sector. The predicted masses, widths, and decay channels presented here provide valuable insights and guidance for experimental searches and future investigations in this field, especially with the update of high luminosity of LHC.

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Correction: The term “branch ratio(s)” has been corrected to read “branching ratio(s)” in various locations in text.